Reversibility of Arctic Sea Ice Retreat - A Multi-Scale Modeling Approach

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Motivation

Arctic summer sea ice has been retreating rapidly over past decade. Climate model projections show further retreat under typical forcing scenarios [1]. The mode of the retreat is a matter of debate. Low-order models show reversible and irreversible retreat depending on the shape of the albedo parametrization [2]. Climate models do not show irreversible sea ice losses, but generally underestimate the current trend of retreat [3,4].

Model

A regular network model was developed to study the local and regional effects of various albedo parametrizations (see box on right) on system dynamics. The ocean mixed layer is modeled as a grid of coupled cells with heat exchange and phase transition. The model grid is forced by longwave, shortwave and lateral atmosheric fluxes and coupled to a constant temperature ocean (Fig.1) [5].

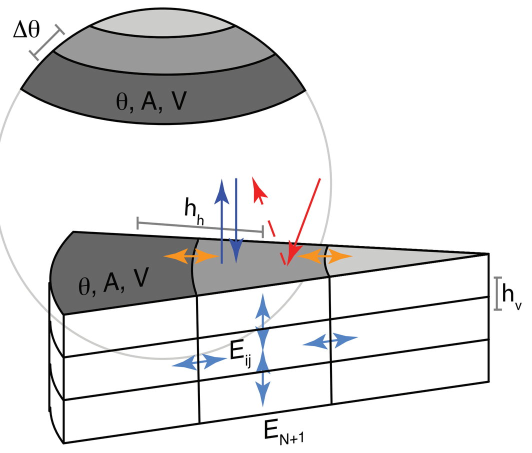

Fig.1: Conceptual image of the regional scale model. Cell parameters are adjusted to latitudinal location. Cells exhange energy with nearest neighbors.

(Ir-)Reversibility

If the model is used to simulate a spatially confined section of ocean mixed layer with a sharp step-like albedo transition between ice and water, the result are irreversible sea ice losses when forcing is increased (Fig. 2) [2].

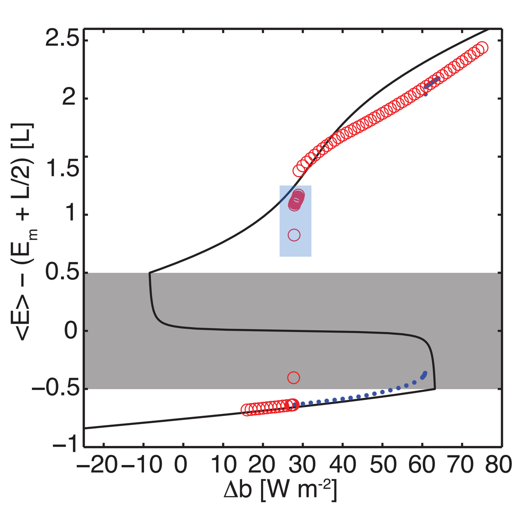

Fig.2: Avg. cell energy vs additional atmospheric forcing for a spatially confined model. Ice covered initial conditions (blue) transition to open water only under high forcing. Open water initial conditions (red) transition to ice covered conditions under much lower forcing.

Used as a regional scale model (latitude 60°N to 90°N) with a similar albedo transition, no structurally stable bistability is found. Summer sea ice retreat exhibits a sudden, but reversible transition from summer ice extent at latitude 83°N to a complete loss of summer sea ice (Fig.3) [5].

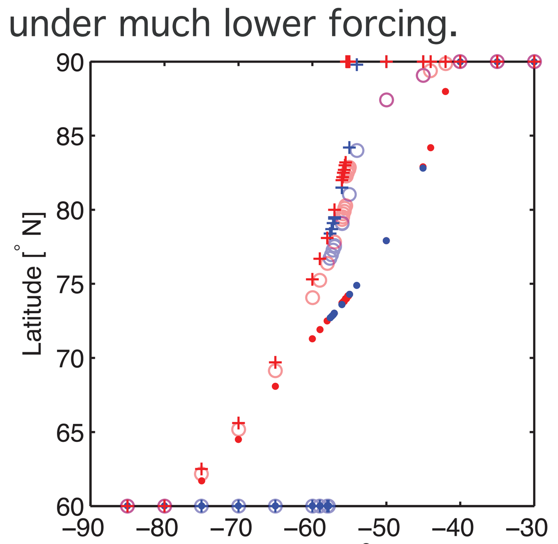

Fig.3: Ice edge latitude vs forcing for the regional model. The summer ice extent (plus signs) suddenly transitions to an open water condition. The winter ice extent (dots) slowly retreats with increased forcing.

The lack of structurally stable bistability in the regional model suggests that lateral oceanic heat fluxes extinguish bistability.

Indicators of Change

Change in the state of the Arctic sea ice cover is most often reported in terms of ice extent measured using satelites (Fig. 4a, blue)[6]. More indicative of the total energy in the system is the total ice volume which can only be obtained by combining measurements and models (Fig. 4a, black)[7].

An inverse thickness measure (ice extent divided by ice volume) is used to highlight changes of a thinning sea ice cover (Figs. 4a-6a). This measure reveals changing ice thickness regimes (Fig. 4b) in the record low ice extent (2007) and ice volume years (2010, 2011). In 2007, the inverse thickness exhibits a 'shoulder' at half peak height, indicating the thickening of the remaining ice cover. Then the measure spikes towards the end of 2007 indicating that a much larger amount of very thin ice is in the system than in previous years. In 2010 and 2011, the shoulder at half peak height is replaced by a double peak. This indicates, that thin ice is growing, but this ice is not thickening much as it grows.

Comparison of simulations resulting in stable summer ice cover (Fig. 5) and a retreating summer ice cover (Fig. 6) reveal a regime change. Figs. 5a and 6a show a 20 year record of the inverse thickness measure. For the unstable summer ice cover a shoulder at half peak height develops into a double peak (Fig. 6a) as the summer ice edge (Fig. 6b) receeds northwards.

The inverse thickness (Figs. 5c and 6c) and ice thickness over the latitudinal model extent (Figs. 5d and 6d) shows that: i) much of the seasonal ice retreat is due to a process of retreat through thinning; and, ii) the unstable summer ice extent case (Fig. 6) exhibits significant lateral retreat of the ice cover without previous thinning. As the ice cover rebounds to its winter ice extent, in the stable summer ice cover case the ice extent increases and the new ice thickens at the same time. In the unstable summer ice extent case, the ice cover the ice extent increases, but the new ice thickens much slower.

The double peak in Figs. 4b and 6a is generated by the same mechanism. This indicates that the current Arctic summer ice extent may be unstable.

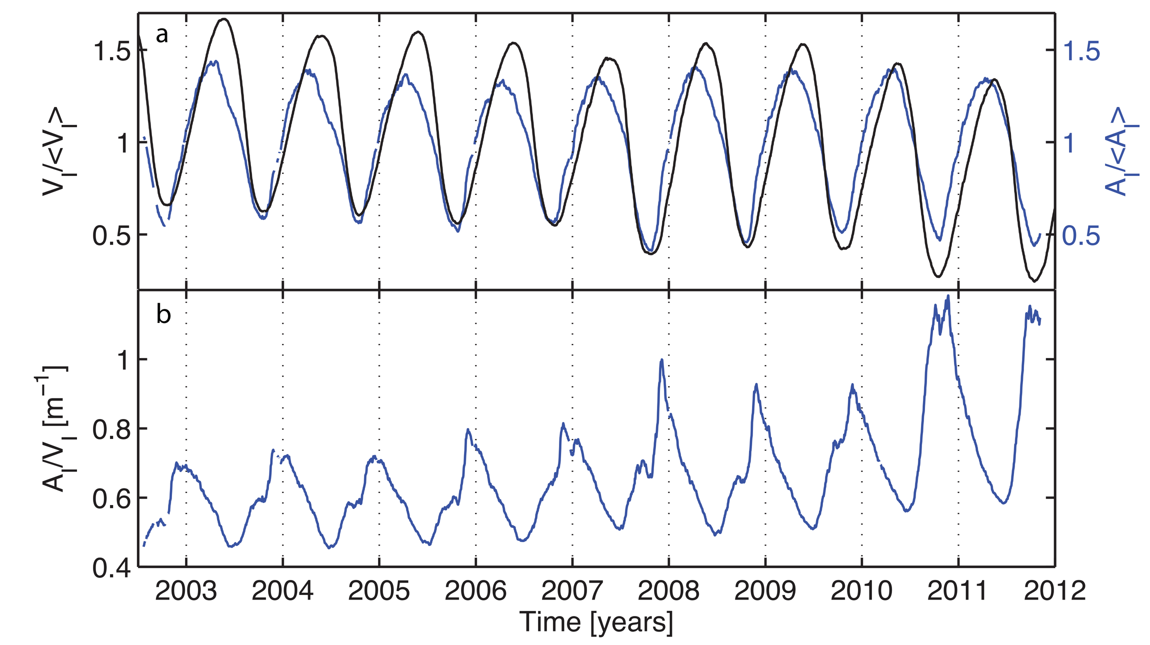

Fig.4: a) Normalized ice extent (blue) [6] and normalized ice volume (black) [7] vs time.
b) Inverse ice thickness measure (extent/volume) vs time.

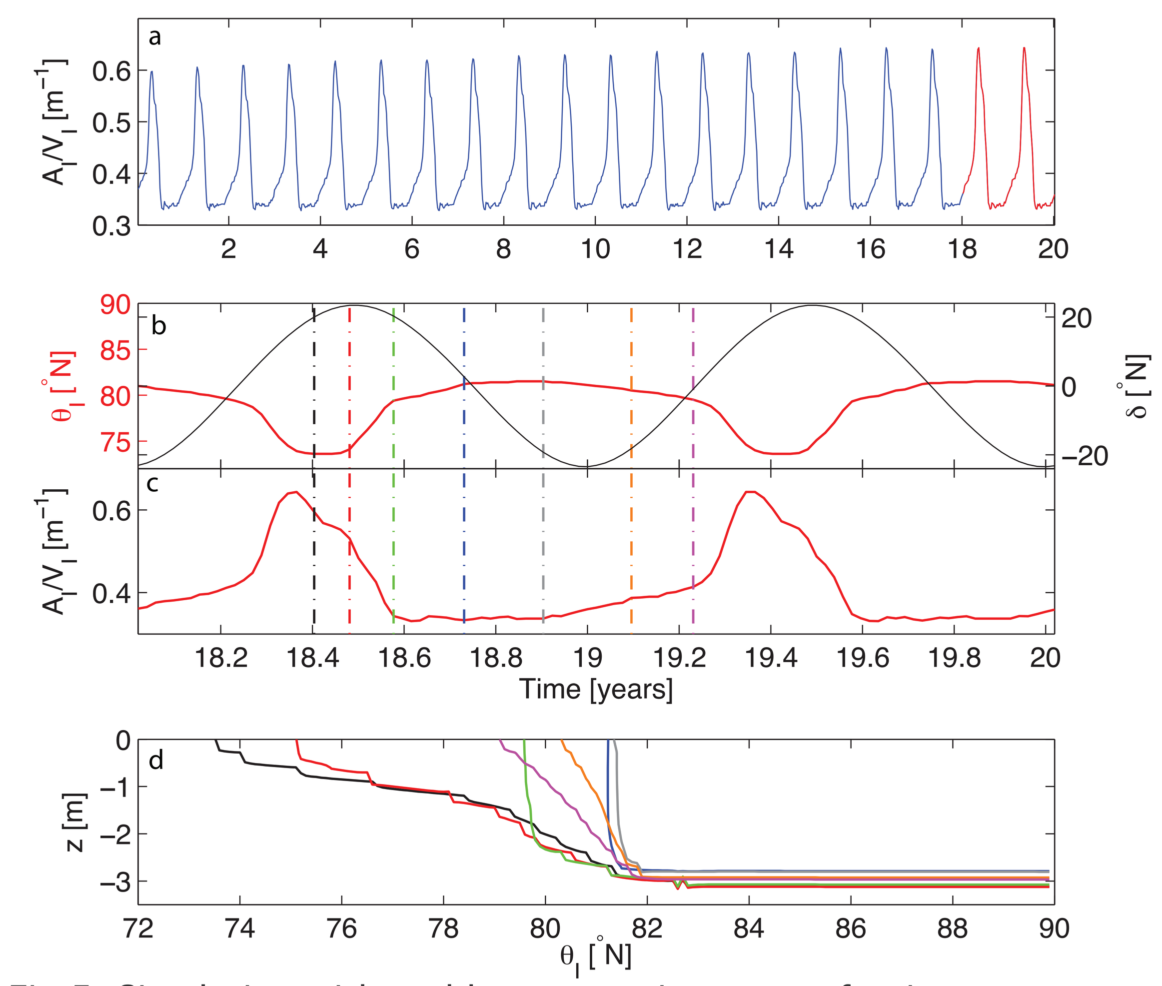

Fig.5: Simulation with stable summer ice cover, forcing $\Delta b = -56\ \mathrm{W\ m^{-2}}$ (cf. Fig. 3).
a) Inverse ice thickness measure (extent/volume) vs time.
b) Ice edge latitude (red) and solar declination (black) vs time.
c) Inverse ice thickness measure vs time, last two seasonal cycles from a.
d) Ice thickness vs latitude for various times of the year. Colors correspond with colors of vertical lines in b and c.

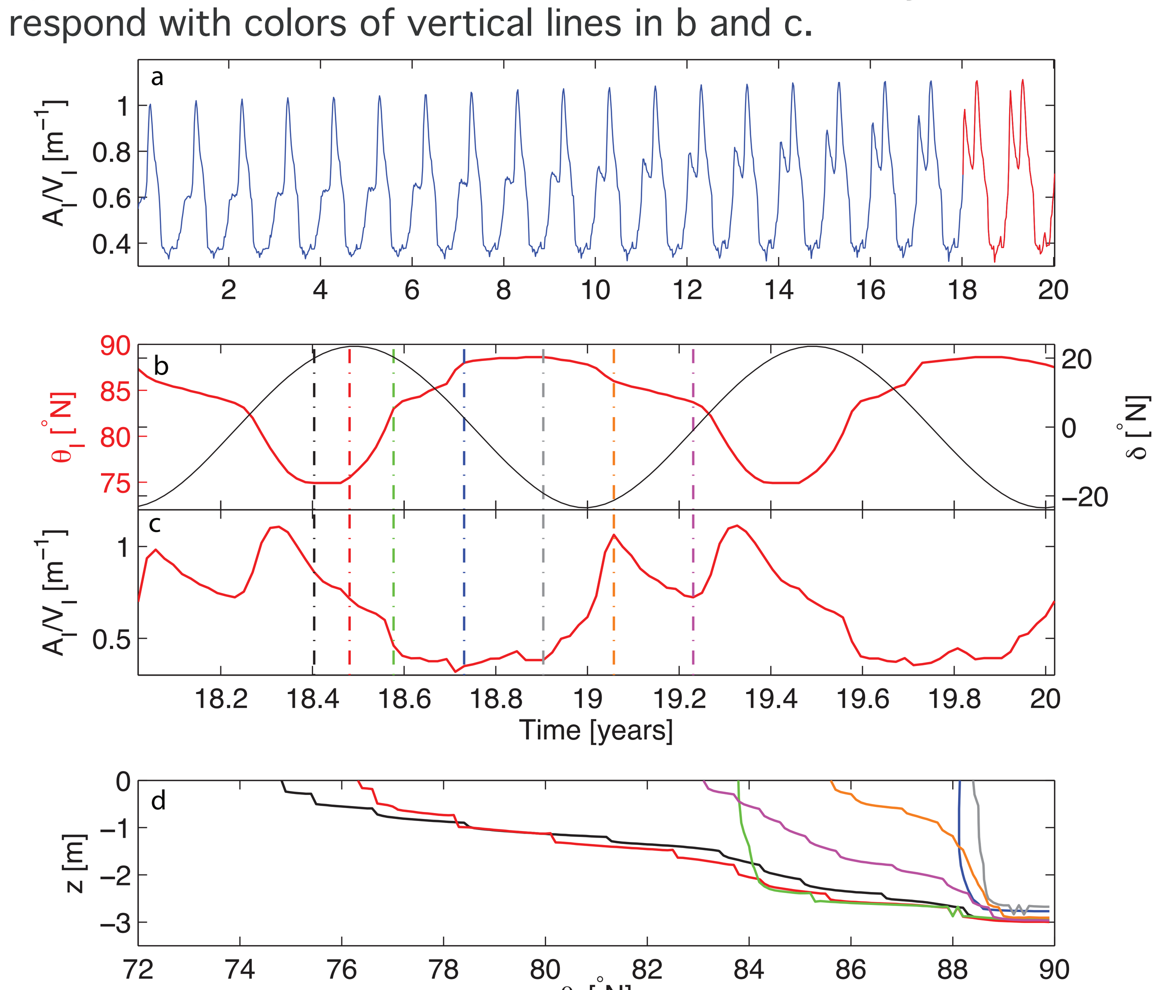

Fig.6: Simulation with unstable summer ice cover, forcing $\Delta b = -54\ \mathrm{W\ m^{-2}}$ (cf. Fig. 3).
a) Inverse ice thickness measure (extent/volume) vs time.
b) Ice edge latitude (red) and solar declination (black) vs time.
c) Inverse ice thickness measure vs time, last two seasonal cycles from a.
d) Ice thickness vs latitude for various times of the year. Colors correspond with colors of vertical lines in b and c.

Ice Albedo Feedback

Sea ice has a high albedo, i.e., it reflects shortwave radiation very well. Open ocean has a low albedo and effectively absorbs shortwave radiation. When ice and open water exist beside each other this can cause a feedback loop where the energy absorbed in the open water causes adjacent ice to melt. This results in more open ocean absorbing more energy.

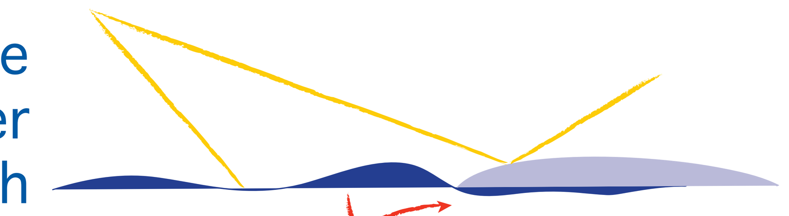

Fig. 7: Conceptual image of ice albedo feedback.

The transition from ice to ocean albedo can have a significant effect on the feedback mechanism and the local [2] and regional [5] dynamics of a retreating ice cover.

Comparison with data from the SHEBA experiment (Fig. 8a, blue and red markers) [8,9,10] motivates locally relatively sharp albedo transitions around the melting point.

It has been shown for spatially confined (local) models that sharp albedo transitions result in irreversible sea ice retreat. Softer albedo transitions reduce or extiguish the structurally stable bistability in such models.

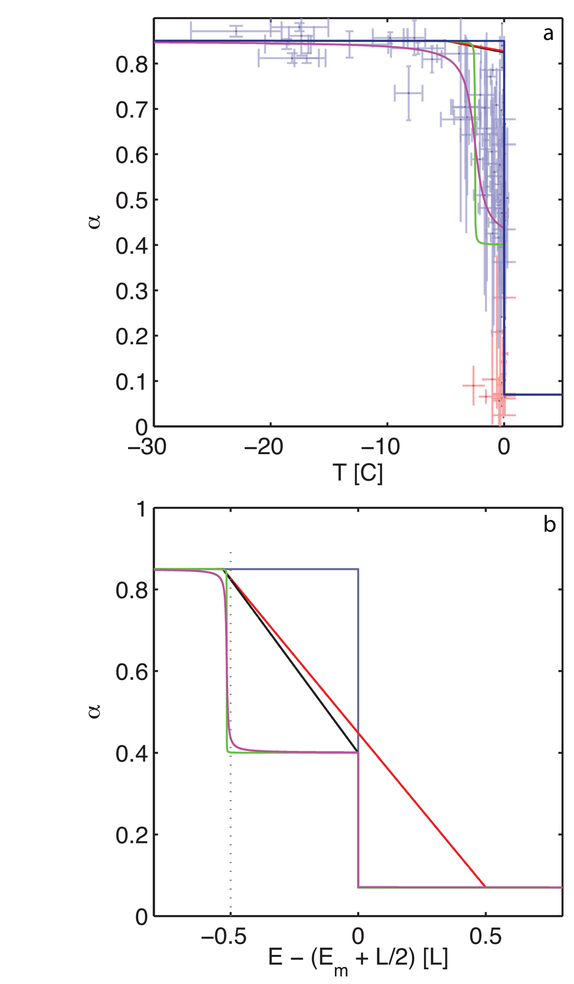

Fig. 8: a) Albedo vs Temperature. Ice albedo data (blue), open water (red). Albedo parametrization used for Figs. 3, 5, and 6 in purple.
b) Various albedo parametrizations vs surface cell energy.

Conclusion

The regular network model presented can serve to connect results from low-order and climate models (GCMs).

Bistability observed in the spatially confined model version under sharp step-like albedo transitions is extiguished in the regional model due to lateral coupling.

The model can serve to identify indicators of change under controlled conditions and allows to study the isolated effects of changes to specific parametrizations such as albedo or longwave forcing.

References
[1] IPCC Fourth Assessment Report, 2006; [2] M. Mueller-Stoffels and R. Wackerbauer, Nonlin. Proc. in Geophysics, 2012; [3] K. Armour, et al., Geophys. Res. Letters, 2011; [4] J. Stroeve, et al., Geophys. Res. Letters, 2007; [5] M. Mueller-Stoffels, Dissertation, UAF, 2012; [6] IARC-JAXA Information Systems, AMSR-E Satelite Record, 2012; [7] Polar Science Center, PIOMAS Model Data, 2012; [8] D. Perovich, et al., SHEBA Ice Albedo Data, 1998; [9] C. Paulson, SHEBA Lead Albedo Data, 1998; [10] E. Andreas, et. al, SHEBA Near-surface Temperature Data, 1998.